Lagrangian Turbulence and Transport in Semi-enclosed Basins and Coastal Regions

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LONG-TERM GOALS

The long-term goal of this project is the development and application of new methods of investigation for the use of Lagrangian data and other emerging in-situ and remote instruments (drifters, HF radar, gliders and satellite) that provide information on upper ocean advection. Special attention is given to the development of new techniques for data analysis and assimilation in Eulerian numerical models for the prediction of Lagrangian transport in coastal flows.

OBJECTIVES

The project has the following specific objectives pursued during the last year of funding:
1) To use methods for velocity reconstruction from model outputs and drifter data to improve the prediction of sonobuoy trajectories in an operational setting.
2) To use HF radar and drifter data to characterize and predict transport properties in coastal flows.
3) To participate to the planning, execution and data analysis of a Rapid Environment Assessment experiment in the coastal ocean (Ligurian Sea, Mediterranean Sea).

APPROACH

The work involves a combination of analytical, numerical and data processing techniques as well as participation to experimental work planning. The method development and application have been carried out in collaboration with our long standing collaborator L. Piterbarg (UCSC), as well as with researchers from NRL (P. Hogan), University of Delaware (D. Kirwan), University of Toulon (A. Molcard), CNR (V. Taillandier, G.P. Gasparini), University of Naples (E. Zambianchi). The experimental work has been done together with an international team lead by NURC-NATO (C. Trees, M. Rixen).

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WORK COMPLETED

1) Publication of a paper on the development and application of a fusion method for tracer data from satellite and model outputs (Mercatini et al., 2010).

2) Publication of a paper on assimilation of Argo floats in an operational model system (Taillandier et al., 2010).

3) Publication of a paper on the identification of transport pathways in a coastal area using data from VHF radar and drifters (Haza et al., 2010).

4) Publication of a paper on the dynamics of a coastal buoyant current in presence of wind forcing (Magaldi et al., 2010).

5) Submission and final revision of a paper on velocity reconstruction from model outputs and drifter data to improve the prediction of sonobuoy trajectories (Chang et al., 2010).

6) Submission of a paper on relative dispersion computed from drifter data during two Marine Rapid Assessment Experiments (MREA 2007-2008) (Schroeder et al., 2010).

RESULTS

i) Prediction of sonobuoy trajectories using velocity fields reconstructed using model outputs and drifter data

The method for velocity reconstruction using Lagrangian drifter data developed during the previous grant periods (Taillandier et al., 2006, 2008) has been applied to the problem of sonobuoy prediction using a unique data set collected from an exercise off Taiwan in October 2007 (Chang et al., 2010). The data are composed of 30 SVP drifters and 29 sonobuoys with instrumented chains deployed in a small grid (approximately ½ degree square) over three days during a Littoral Warfare Advanced Deployment (LWAD07) experiment. In addition to this data, hindcasts for the experiment are provided from a data assimilating model, the Naval Research Laboratory East Asian Sea 1/16 degree ocean model (EAS-16). The velocity field has been reconstructed by blending the outputs of EAS-16 with the data from the SVP drifters and then by statistically projecting the velocity correction over the upper water column. The corrected velocity fields have then been used to compute sonobuoy trajectories using an appropriate drag model, and the results are compared with the observed sonobuoy trajectories.

The work has been done in collaboration with the University of Delaware and two different velocity reconstruction methods have been tested. On the one side we (RSMAS group) have used the Lagragian Analysis Variational method (LAVA) previously developed in the framework of the present grant and directly based on trajectory information, while the University of Delaware has tested a method based on Normal Mode Analysis (NMA) that uses velocity computed from the drifters (Toner et al., 2001).

The investigation has a number of novel and interesting aspects. It provides an example of a truly operational application, targeted to predict the motion of sonobuoys within the framework of an LWAD exercise. The region of application is interesting and challenging, since it is located along the shelf break at the boundary of the Kuroshio, so that the meandering of the current can induce the presence of two different regimes in a relatively small area, divided by a sharp front. Predicting the exact location of the front at such scales is challenging for a numerical model. Also, the use of two different methods of reconstruction provides an interesting opportunity to compare results and pros and cons of different approaches. Finally and mostly important, the present application provides a first example of *independent testing* of the reconstruction results, since the reconstruction is based on drifter data only while the testing is performed using the sonobuoys trajectories. Sonobuoys not only respond differently to currents than drifters do, but they also have been launched at slightly different times (order of one day difference) from the drifters, which is significant for Lagrangian applications characterized by time scales of 1-2 days.

A test of internal consistency of the reconstruction methods was first performed, considering the SVP drifter trajectories. Results are shown in Fig.1 comparing the in-situ trajectories with those based on the EAS-16 model without corrections (left panel) and based on the LAVA corrected fields (right panel). While the EAS-16 trajectories do not reproduce the two dynamical regimes of the Kuroshio and of the shelf, that are present in the in-situ trajectories, the LAVA trajectories appear quite similar to the observed ones and show the dramatic difference between the two regimes. The result is quantified in terms of rms error on particle location as shown in Fig.2, where also the results for NMA correction are shown. As it can be seen, the error is significantly decreased by both the correction methods, with a gain of approximately 75% for LAVA and 55% for NMA.

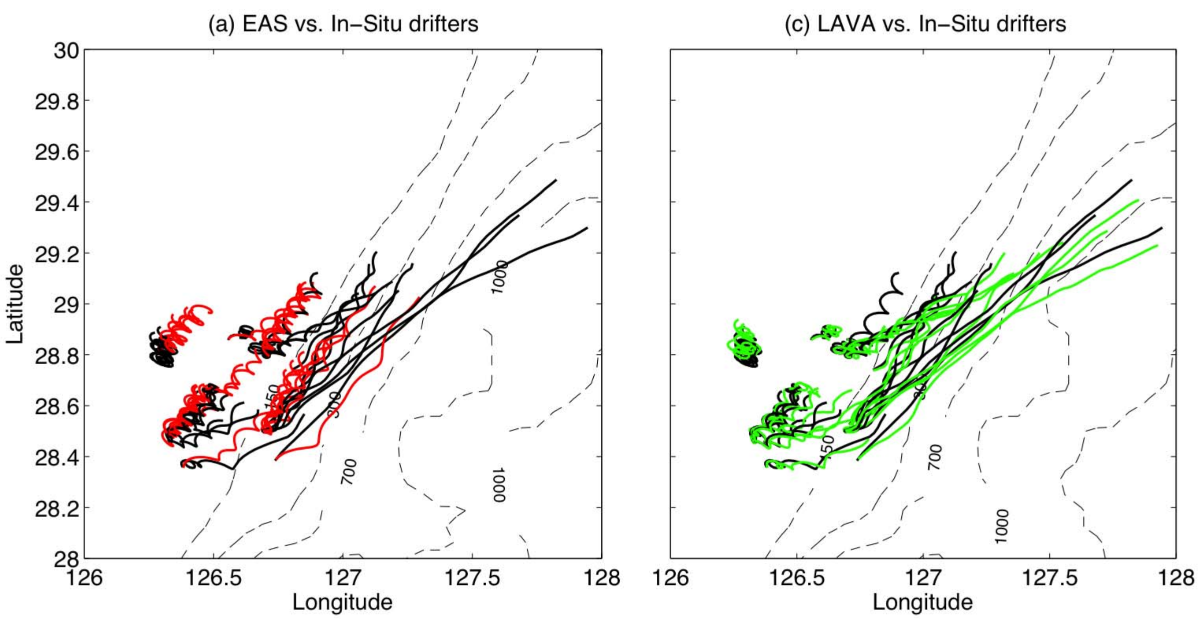

Figure 1. Comparison of observed drifter trajectories (black) with trajectories computed using the EAS-16 velocity without corrections (red, left panel), and the LAVA corrected velocities (green, right panel).

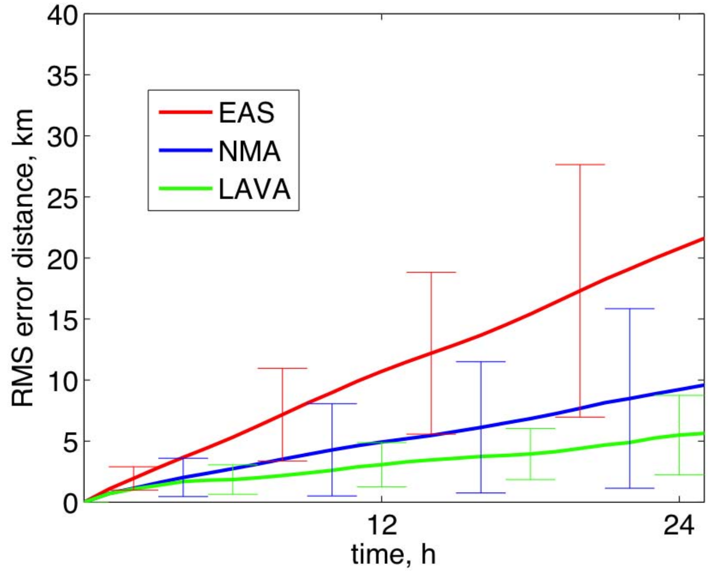

Figure 2. Comparison of rms error for drifter trajectories computed using the EAS-16 velocity without corrections (red), NMA corrected (blue) and LAVA corrected velocity (green). Time is measured from each drifter launch. Error bars show standard deviation.

A similar analysis has then been performed considering the independent sonobuoy data set. Visual results for sonobuoy trajectories are shown in Fig.3, while the error metric is shown in Fig.4. As for the drifters, both LAVA and NMA based trajectories are qualitatively much more similar to the observed ones than the EAS-16 based ones. Quantitatively, the error for sonobuoys decreases less than for the drifters, but still significantly: approximately 50% for LAVA and 25% for NMA. Both methods provide very significant improvement in reconstructing the sonobuoy trajectories, but the better performance of LAVA suggests that the use of trajectory-based corrections might be more effective for Lagrangian prediction than relying on derived velocities.

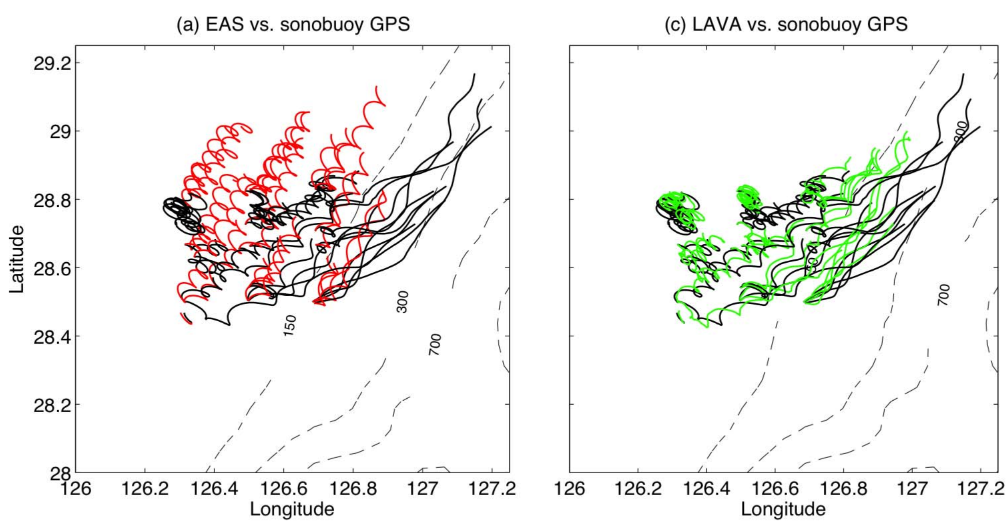

Figure 3. Comparison of observed sonobuoy trajectories (black) with trajectories computed using the EAS-16 velocity without corrections (red, left panel), and the LAVA corrected velocities (green, right panel).

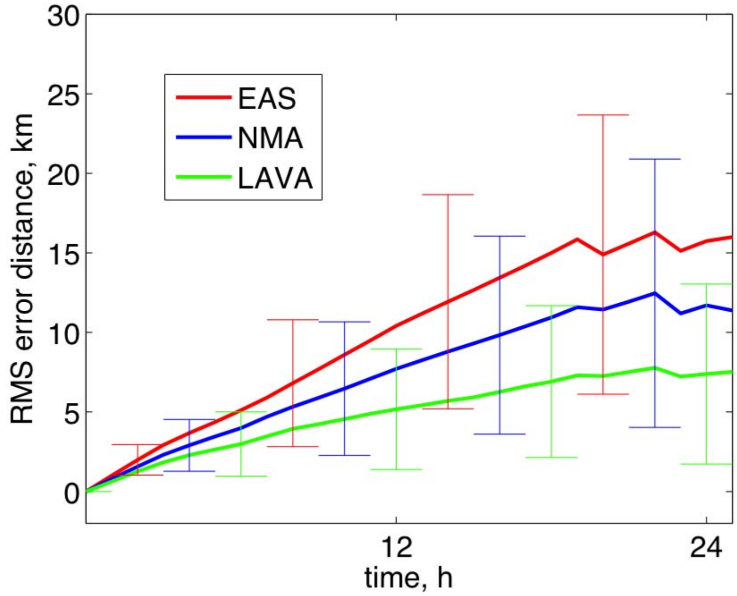

Figure 4. Comparison of rms error for sonobuoy trajectories computed using the EAS-16 velocity without corrections (red), NMA corrected (blue) and LAVA corrected (green) velocity. Time is measured from each sonobuoy launch. Error bars show standard deviation.

ii) Use of VHF radar and drifter data to study transport pathways and dispersion in coastal flows

During previous years (2007 and 2008) VHF radar and drifter data have been collected as part of Marine Rapid Environmental Assessment (MREA) experiments in the Ligurian Sea (a subregion of the Mediterranean Sea). These data have been analyzed during the present grant period, focusing on the identification of transport pathways and dispersion characteristics in coastal flows at various scales, from the regional sub-basin scales (order of 100 km) to the very coastal scale of the Gulf of La Spezia (less than 10 km).

At the regional scale, the analysis has been performed using clusters of surface drifters repeatedly deployed from the same location, approximately in the center of the basin, during different months in 2007 and 2008 respectively (Schroeder et al., 2010). The clusters have initial radii of less than 1 km, or an order of magnitude below the typical deformation radius (of the order of 10-20 km). The data set consists of 45 original pairs and more than 50 total pairs (including chance ones) in the spatial range between 1 km and 200 km. NCOM model results have been used to complement the data and to quantify errors arising from the sparse sampling in the observations.

Relative dispersion have been estimated using the mean square separation of particle pairs, $D^2(t)$, and the Finite Scale Lyapunov Exponents (FSLEs). The two metrics show broadly consistent results, indicating in particular a clear initial time exponential phase with an e-folding time scale between 0.5 -1 days, or Lyapunov exponent in the range of 0.7-1 days^{-1}. This result is shown in Fig.5 for the example of $D^2(t)$ for 2007, where the red line indicates the linear fit corresponding to the exponential behaviour in the semi-log plot. The exponential phase extends for 4-7 days in time and between 1 km and 10-20 km in separation scale.

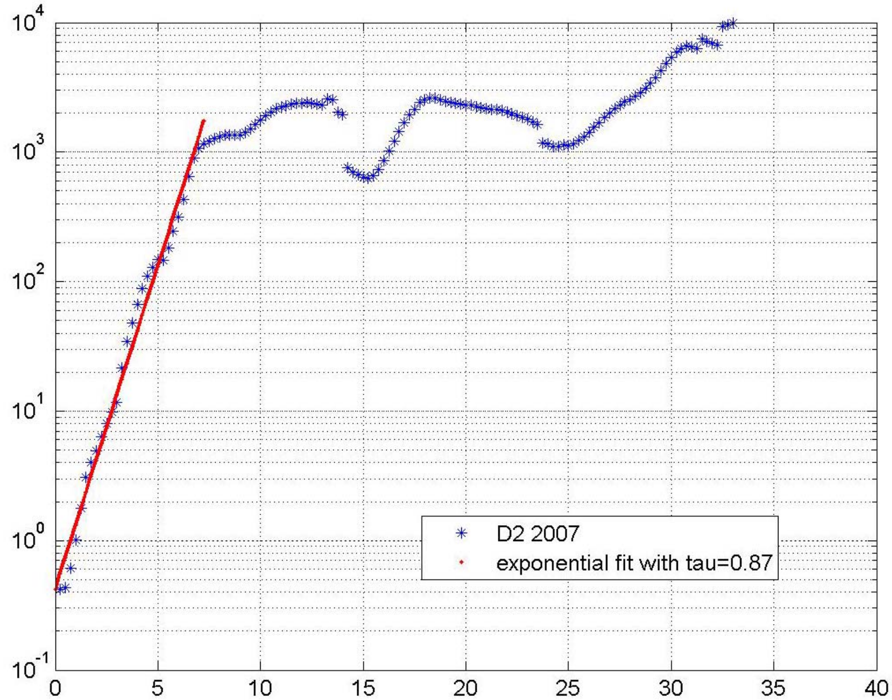

Figure 5. Relative dispersion $D^2(t)$ as a function of time in a semi-log plot for drifter pairs in 2007. Red line indicates the linear fit corresponding to an exponential behavior.

To our knowledge, this is only the third time that an exponential regime is observed from drifter data. Our results are consistent with those of Lacasce and Ohlman (2003) and Koszalka et al. (2009), who found an exponential regime in the Gulf of Mexico and in the Nordic Seas, respectively. Markedly different results, instead, have been found by Lumpkin and Ellipot (2010) in the Gulf Stream region, who find that the initial phase is characterized by a power low rather than by an exponential. The reasons for this difference are not clear at the moment and needs further investigation. It might be due to the difference in geographical regions, characterized by different dynamical properties (e.g. Griffa et al., 2008), or it might be due to unusual (storm) conditions occurring during the Gulf Stream launches.

The initial exponential regime is suggestive of the fact that relative dispersion is predominantly nonlocal, i.e. it is controlled by mesoscale dynamics rather than by submesocale eddies directly sampled by the drifter pairs. This is consistent also with the patterns of the trajectories in the clusters and with the velocity field as sampled by the drifters. Semi-permanent mesoscale structures and recirculations with scales of the order of 10-20 km are clearly visible in the velocity field, and most of the drifters appear to be initially captured inside them, moving coherently together and progressively separating until they reach the scale of the recirculations. This result has important practical applications, for instance for instance for warfare issues or in case of pollutant spreading. We can expect that an initial patch will tend to grow initially maintaining an approximately coherent structure and increasing its size exponentially with a doubling time of approximately 0.5-1 days, until it reaches a size of approximately 20 km. This is very relevant for action planning and mitigation.
Dispersion properties and transport pathways have also been studied at the scales of the Gulf of La Spezia (Haza et al., 2010), a 5 km by 10 km feature along the Ligurian coast, using data from a VHF

radar system operated by the University of Toulon during two weeks in the summer of 2007 with 250 m and 15 min resolution. Clusters of CODE surface drifters have also been launched during this period in collaboration with OGS and CNR. The surface drifters are found to follow the temporal and spatial evolution of the Finite Scale Lyapunov Exponents (FSLEs) computed from the radar velocity fields, indicating the precision of both the VHF radar measurements and the diagnostic FSLE in mapping accurately the transport pathways. In light of this agreement, an analysis of the relative dispersion has been conducted using the radar data. It is found that the average FSLE value varies within a narrow range of 4-7 day^{-1}, and displays an exponential regime over the entire extent of the measurements. This indicates, that even at these small coastal flows, relative dispersion is controlled non-locally, namely by slow, persistent, energetic mesoscale structures as opposed to the rapidly-evolving high-gradient small-scale turbulent features.

iii) Planning and participation to the Marine Rapid Assessment Experiment LIDEX10

During 2010, we have been involved in the planning and execution of a new experiment, the LIDEX10 experiment, focused on a specific region in the eastern Ligurian Sea, outside from the main cyclonic circulation and characterized by the presence of small scale surface fronts. Results from the 2007-2008 observations (Schroeder et al., 2010) suggest that the few drifter pairs that left the main circulation and got stranded in this area might be characterized by different dispersion properties and possibly influenced by submesoscale processes. The experiment was specifically targeted to:

a) study of relative dispersion in an area with high variability and small scale surface fronts;

b) collect the heterogeneous data sets (drifters, gliders, HF radars, model outputs) to test new methodologies for analysis, fusion and assimilation.

The Ligurian Dispersion Experiment LIDEX10 has been performed in collaboration with the NURC-NATO REP10 (Recognized Environmental Picture) exercise, and with an extensive international partnership, including NURC, CNR, OGS, INGV, University of Toulon, University of Naples, ENSTA-CNRS.

We have been directly involved in the design of the experiment. In particular, drifters have been launched in clusters formed by unstructured triplets, in order to sample various initial scales, from 50 m to km, as shown in the schematic in Fig.6 (left panel).

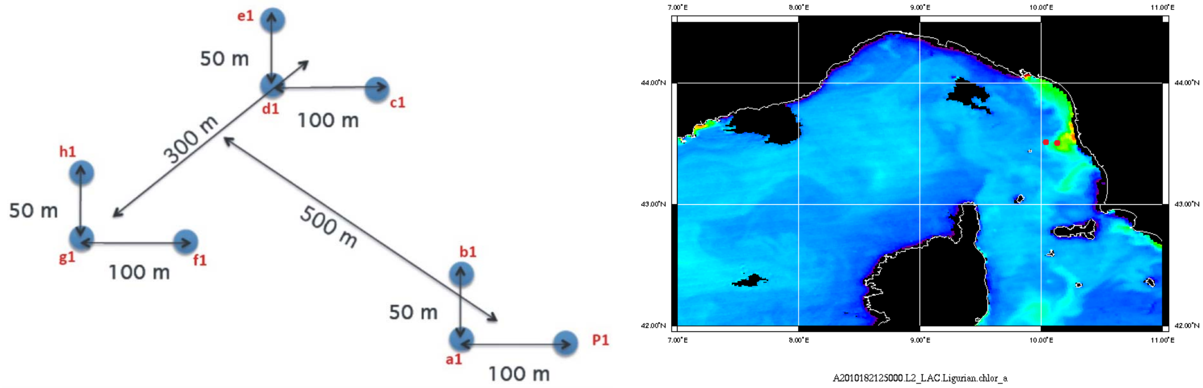

Fig. 6: Schematic of drifter cluster (left panel). The design is based on triplets, covering scales from 50-100 m (3 small triplets) to 300-700 m (large triplets). MODIS satellite image (right panel) with superimposed points of cluster release (red dots), courtesy of Chuck Trees, NURC-NATO.

The experiment took place during the summer 2010. Two clusters of 9 drifters each were launched at approximately 5 km distance, on the two sides of a surface front detected by both satellite images and hydrographic casts (Fig.6, right panel). The evolution of the clusters has been followed for more than 2 weeks (Fig.7, left panel), during which a high resolution (less than 1 km) ROMS model was run in real time by NURC. At the same time a glider from INSU-CNRS was piloted to follow the clusters, providing information on temperature, salinity, oxygen and chlorophyll along the path (Fig.7, right panel).

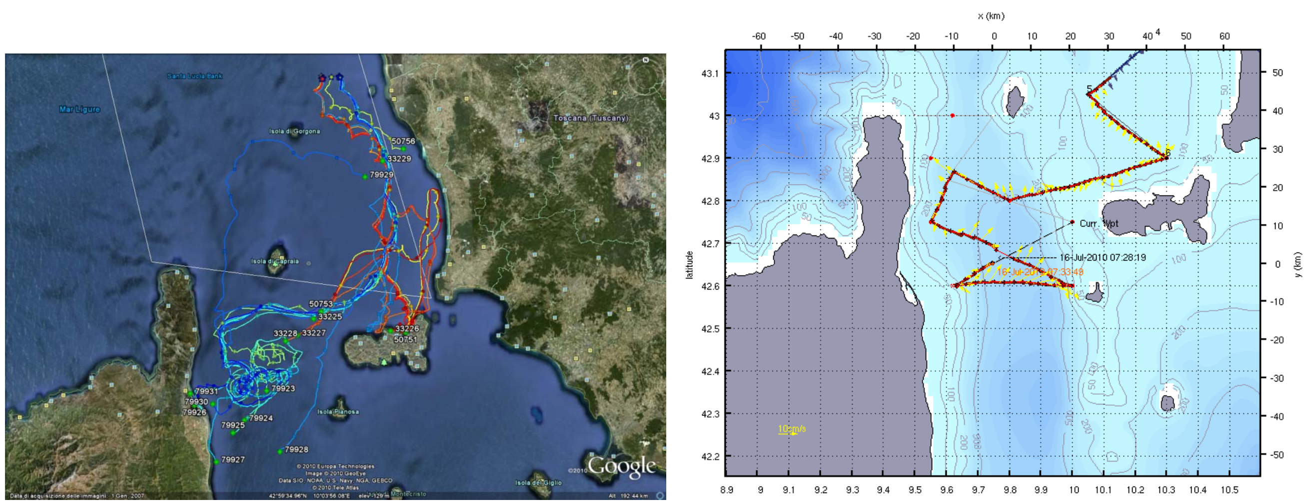

Fig.7: Trajectories of drifters (left panel) during the first 16 days of the LIDEX experiment. Example of glider path (right panel) following the drifter clusters. Courtesy of L. Mortier, P. Testor (ENSTA, CNRS).

The data set is presently available to us, and it is expected to provide a unique opportunity to test methodologies as well as to study sub-mesoscale dynamics, thanks to the high resolution coverage of different instruments and models.

IMPACT/APPLICATIONS

The results on Lagrangian data assimilation and fusion have a significant impact for operational systems and they provide additional value to data from drifters, HF radars, satellites and gliders especially for coastal applications. The results on dispersion and transport pathways provide information on the behavior of tracer patches or floating instrument clusters, with implications for experimental and warfare planning and best sampling.

RELATED PROJECTS

Predictability of particle trajectories in the ocean, ONR, PI: T.M. Özgökmen, N00014-05-1-0095.

Statistical and stochastic problems in Ocean Modeling and Prediction, ONR, PI: L. Piterbarg.

N00014-99-1-0042. How well do blended velocity fields improve the prediction of drifting sensor tracks? PI: A. Griffa, subcontract from University of Delaware.

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